MICRO CATHODE ARC THRUSTER FOR PHONESAT: DEVELOPMENT AND POTENTIAL APPLICATIONS

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ABSTRACT

NASA Ames Research Center and the George Washington University are developing an electric propulsion subsystem that will be integrated into the PhoneSat bus. Experimental tests have shown a reliable performance by firing three different thrusters at various frequencies in vacuum conditions. The interface consists of a microcontroller that sends a trigger pulse to the Pulsed Plasma Unit that is responsible for the thruster operation. A Smartphone is utilized as the main user interface for the selection of commands that control the entire system. The propellant, which is the cathode itself, is a solid cylinder made of Titanium. This simplicity in the design avoids miniaturization and manufacturing problems. The characteristics of this thruster allow an array of µCATs to perform attitude control and orbital correction maneuvers that will open the door for the implementation of an extensive collection of new mission concepts and space applications for CubeSats. NASA Ames is currently working on the integration of the system to fit the thrusters and the PPU inside a 1.5U CubeSat together with the PhoneSat bus. This satellite is intended to be deployed from the ISS in 2015 and test the functionality of the thrusters by spinning the satellite around its long axis and measure the rotational speed with the phone gyros. This test flight will raise the TRL of the propulsion system from 5 to 7 and will be a first test for further CubeSats with propulsion systems, a key subsystem for long duration or interplanetary small satellite missions.

1 INTRODUCTION

The design of micro-propulsion devices that permit complex maneuvers appears as a very promising technology for the near future. Pulsed Plasma Thrusters (PPTs) are one of the most interesting options due to their low requirements in terms of mass, volume and power. In addition, the utilization of a solid propellant facilitates the selection of this type of electric propulsion among others that might require a breakthrough in the miniaturization process for chambers, feed systems and valves.

The µCAT CubeSat integration is a joint effort between NASA Ames and The George Washington University that has shown successful results in the latest tests. The system is compatible with the PhoneSat bus and it accommodates several thrusters that fire at various frequencies. The interface has already been designed for a prototype laboratory version and the next step is the development of a Printed Circuit Board (PCB) that can potentially fly in a CubeSat.

This paper presents the current status of this electric propulsion system and outline potential applications that could be implemented in a 1.5U CubeSat. Preliminary results with basic assumptions are shown in order to assess the feasibility of some of the performances for various missions.

2 STATE OF THE ART MICRO-PULSED PLASMA THRUSTERS

Research in PPTs has been active during the past few years and some of the major complications such as electrode shortcuts or non-uniform propellant ablation have been overcome. Several prototypes have shown consistent results in laboratory tests. However, only a few have been implemented into actual missions and more space-based tests are required in order to validate this technology as a solid and reliable small satellite subsystem. Currently, the Technology Readiness Level (TRL) of the various electric propulsion systems is not high. An improvement in the miniaturization process is necessary in order to fabricate devices that can offer reliable functionality at low cost. Some of the devices that run the Pulsed Plasma Unit (PPU) need to be scaled down efficiently in order to obtain the same performance than in the current laboratory prototypes that use regular breadboards and large external power supply units. Components and devices such as capacitors, inductors and microcontrollers need to validate their reliability in their miniaturized version. In addition, these potential subsystems need to comply with the strict volume and power requirements from CubeSats.

The system needs to be powered in order to release a large amount of energy between the electrodes. Therefore, power constraints are a major limitation in the design of PPTs. Currently, small satellites and CubeSats in particular do not have enough power supply to produce the large discharges that lead to the generation of the desired thrust. The breakdown voltage for the creation of an arc is very large, more than 1kV, which is not supported by the satellite power bus. Hence, it is necessary to incorporate a generator or transformer in the design that converts a low voltage into a pulsed, high voltage discharge [1]. Most of the power buses of a 1U CubeSat provide voltages that typically range from 3.3 to 10 V. Therefore, in order to achieve the previously mentioned breakdown voltage, a generator is required to increase the input magnitude. The settlement of capacitors in series is one of the simplest designs.

The performance of the thruster relies on the electrode configuration. There are semi-empirical laws that depend on the electrode shape. For a coaxial electrode configuration, Gessini et al. [3] performed an analysis with real data from several thrusters. They studied the dependence between energy, impulse bit and electrode geometry. A new semi empirical law that relates impulse bit and energy per pulse was found:

$$I_{bit} \approx 17.5 \cdot E^{1.5} \quad (1)$$

In addition to the electrode configuration, one of the most important parameters in a Pulsed Plasma Thruster is the change in momentum per pulse or *impulse bit*. The Pulsed Plasma Unit (PPU) is the circuit that leads to the creation of a plasma arc between the electrodes. It sends a pulse that controls the generation of thrust at a sequenced time intervals. Therefore, it has the capability to precise a total impulse by accumulating small impulse bits. The disadvantage is that the impulse bit cannot be determined with high accuracy due to shot variation and the deflection angle of the thrust vector [2]. Experimental discharge current curves can be used to provide an estimation of the impulse bit. The following equation can be calculated by integrating the discharge current curve using a trapezoidal method [4].

$$I_{bit} = \frac{L'}{2} \cdot \int_0^t i^2 \, dt \quad (2)$$

This is the major contribution to the impulse and it is produced by the Lorentz force. The impulse bit depends on the inductance gradient and the discharge current. Both of these parameters are affected at the same time by the energy density provided.

Most thruster prototypes use solid propellant rods. This special type of PPTs is called Ablative Pulsed Plasma Thrusters (APPT) and they present several challenges such as low efficiency, contamination and non-uniform ablation.

One of the main reasons of the low efficiency is that a significant portion of the propellant does not contribute to produce thrust. The surface temperature of the propellant remains higher than the boiling point of the material, creating low speed vapor after the main discharge. Therefore, some of the propellant cannot be efficiently accelerated. Carbonization from Teflon propellant can decrease the lifetime of the thruster. Furthermore, attempts to use other type of polymer propellants failed due to severe carbonization. In addition, contamination is a significant concern for PPT discharges. This problem may affect other components in the spacecraft such as sensitive optical systems.

The temperature of the propellant increases with the number of PPT discharges, until a steady state is reached. There is a correlation between the propellant temperature at discharge and the consumption efficiency. At low temperatures, the propellant consumed per discharge is lower than the steady state value. Maintaining a low propellant temperature during operation increases the efficiency of the system [1].

Recently, some academic and private entities have presented several prototypes. A design developed jointly by Clyde Space, Mars Space and the University of Southampton complies with realistic requirements for nano and pico satellites. The system presents a maximum mass of 500g and a maximum consumption of 10W. It consists of six pulsed plasma thrusters that deliver a total ΔV of 40m/s for station keeping and attitude control maneuvers. Every thruster provides a total impulse of about 133.33Ns, giving a maximum value of 800Ns for the mission scenario. It uses a solid propellant made of Teflon and the design accommodates two configurations: side and breech fed systems. Copper-tungsten is used as the electrode material due to its low electrical resistivity, reduced erosion rates and good mechanical and thermal properties. The shape of the electrodes has a blunted configuration instead of the typical pointed end with the aim of reducing the erosion rate. The charge/discharge unit uses 20 capacitors that are able to store energy of 5J, each one having a capacitance of 200nF. A concentric spark plug with an output voltage from 6 to 8kV is included and is based on the heritage of a previous version. This design is the evolution of a previous miniaturized Pulsed Plasma Thruster that flew in mission FalconSat-3 [4].

Surrey Space Center (SSC) developed an electric propulsion system based on a PPT. The module consisted of eight micro PPTs that flew in the satellite STRAND-1. Four of them were located at the satellite stack and the others at the bottom. The system was designed for fine pointing applications but due to certain complexities, at latter steps the system was modified for performing de-orbiting maneuvers. DC to DC transformers took an input of 5V from the power bus and converted them to 800V in order to charge a high voltage capacitor. The total energy required for this subsystem was 1.5W. However, it was not tested in Space due to a failure in the communication system of the satellite [6].

3 µCAT THRUSTER

3.1 Thruster functionality

The performance of a Pulsed Plasma Thruster is driven by the formation of a plasma arc between a cathode and an anode. Usually, the plasma arc is produced by ablating the surface of a solid material that is placed between the electrodes. Thrust is produced by fully ionized plasma jets that have high velocity. Exhaust speeds in the order of 10^4m/s are achieved and this mechanism can be used as a direct source of propulsion. However, some limitations are presented. The force per pulse is not adjustable for each cathode material and plasma is only directed by the pressure gradient through the thruster channels. Therefore, the thrust directional efficiency mainly depends on the geometry of the electrodes. This is translated into a very low propulsive efficiency that is a characteristic of these devices. Regularly, efficiencies are below 10%.

Micro PPTs can modulate the firing periods in concordance with mission requirements. The control unit sends a trigger pulse that regulates the firing rate. Depending on the received signal, the thruster operates at a specific frequency that determines the amount of thrust provided.

The Micro-Cathode Arc Thruster (µCAT) consists of a very small thruster head (5mm of cross section), electrically powered by a Pulsed Plasma Unit (PPU) that manages the stored energy in an inductor. Vacuum arc discharges ablate the cathode material, forming cathode spots that transfer surface micro-plasma. The system provides a specific impulse in the range of 2000-3500s. The thruster could deliver a Delta-V of 300m/s for a 4kg satellite. The µCAT offers a thrust to mass ratio of 0.63µN/gr and a quasi-perfect ionization degree of 99% of the plasma particles in the exhaust plume, giving a near zero back flux [7]. Therefore, potential hazardous interactions in the electronic equipment of the thruster and other subsystems are avoided.

The PPU is built from various components. A two-part circuit produces the charge/discharge activity that enables the plasma production. The two principal parts of the circuit are an inductor for energy storage and an anode/cathode discharge. A bipolar transistor controls the current flow in both of the sections. The inductor is comprised of a wire-wound inductor of 30 turns of gauge wire on a high flux magnetic core and an electrolytic capacitor that is used as a backup device. The electrodes are cylindrically shaped and concentrically aligned. The plasma flows from an anode made of nickel to a cathode made of Titanium, which also acts as the propellant. A ceramic insulator is placed between the two surfaces. Carbon paint is applied in one of the edges of the insulator in order to enforce the connectivity between both electrodes in that location.

In addition, the incorporation of an external magnetic coil can improve significantly the capabilities of the thruster [7]. The µCAT system was tested at NASA Ames Research Center in 2013 in a vacuum chamber. This test verified the functionality of an interface between PhoneSat and three different micro thrusters in vacuum conditions.

The interface between the PhoneSat Nexus S phone and the thrusters tested in 2013 included a Netburner Mod 240 micro-controller, a power control board and a channel control board and the three PPUs. The entire system was powered by an external power supply. Figure 1 shows a diagram of the main connections.

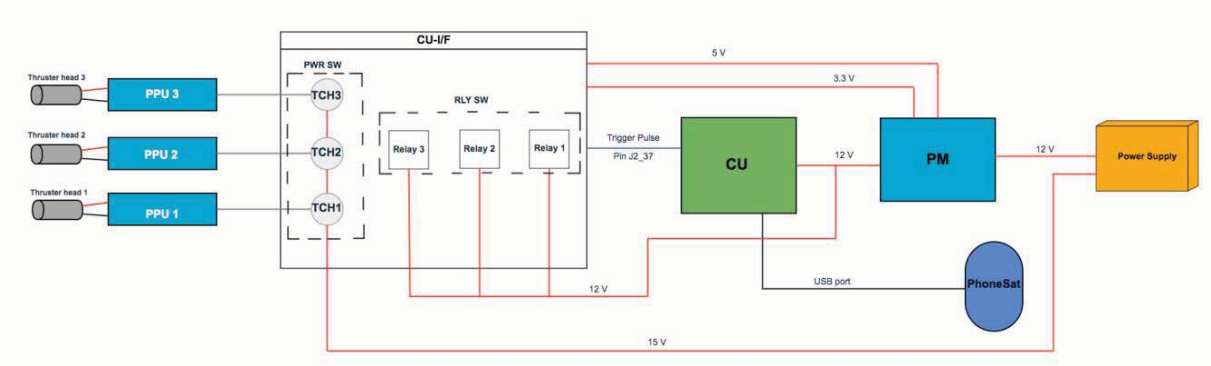

Figure 1: Basic layout of the previous µCAT propulsion system with the PhoneSat interface

3.2 Current status

The Netburner, the power board, the power supply and the control unit interface have been replaced by a smaller version of a microcontroller and batteries. This change has reduced significantly the volume and complexity of the system. The telemetry of the trigger pulse and the selection of an extended range of frequencies are not available in this configuration. However, the thrusters show a solid performance and this improvement paves the way for the miniaturization in a CubeSat scale as the new step.

The designs of the PCB and the optimization of the power range have started. New layouts and designs of the schematics are being done and new components are being tested. The goal is to obtain a board that complies with the PhoneSat requirements in order to be accommodated into a CubeSat bus.

3.3 Experimental Results

The Micro Cathode Arc thruster was tested in the facilities at the University of Southern California (USC) using a torsional thrust stand mass balance. The balance consists of an underdamped, second-order harmonic oscillator and it has a high sensitivity. Impulsive forces in the order of several nano-newton per second can be measured. The stand deflects small angles when tiny forces are applied through. It has flexure springs to proportionate a restoring force to the beam. The dynamics of the stand are controlled by the damping system which is electromagnetic and consists of a set of magnets and a copper plate. The displacement produced by the thrust is measured by a linear variable differential transformer. This device is mounted horizontally on the lever arm of the stand. Therefore, each time the thrust deflects the arm will correspond to an equivalent deflection of the ferromagnetic core that is inside the device. When this component moves inside the device, the inductance of two coils change and it can be measured as a correlation with the position of the thrust stand [8].

During the experimental tests, the thrust stand was modified to accommodate the µCAT. With the final configuration, the thrust stand had a period of 2.74 seconds. The thruster was fired in a quasi-steady state mode to allow the deflection to be measured. The frequency was set to 50Hz and for a single measurement, the thruster was fired 14 times in concordance with the total impulse imparted to the stand to be in the range of one-tenth of the period of the stand. The total thruster impulse for one firing was calculated to be 7.2 ± 0.2e-7Ns [8]. With the implementation of a magnetic coil, the impulse magnitude was higher. With a 0.3T magnetic field applied, the maximum impulse reached 1.1µNs approximately. In addition, a large magnetic field also increases the thruster efficiency. For

a 0.3T magnetic field, it increases about five times. These results support the validity of this propulsion system for small satellite propulsion systems.

4 THE PHONESAT BUS

4.1 PhoneSat previous missions: PhoneSat 1.0 and 2.0

The PhoneSat project at NASA Ames Research Center has already successfully flown 4 spacecraft, 2 PhoneSat 1.0 and 2 PhoneSat 2. The first version of the satellite wanted to answer the commonly asked question of "Does a phone work in space?". With the successful accomplishments of Alexander, Graham and Bell, the next step was to make a fully functional satellite bus, PhoneSat 2. While PhoneSat 1 consisted on a Nexus One phone, a StenSat radio working in the amateur band (437.425MHz) and 12 Li-Ion batteries, PhoneSat 2 added new subsystems: on board power generation, 3 axis ADCS with both magnetorquers and reaction wheels, an upgraded smartphone version, the Nexus S, and a two-way communication system in addition to the StenSat beacon, the Microhard, working on the S-Band.

The two PhoneSat 1.0 flight units flew on the Antares I launch on April 21 2013. Both of them successfully sent health data down to the radio amateur community, took 100 pictures with the smartphone camera and selected the best one, which was sent in small packets over the StenSat radio during the 5 days of orbital lifetime. PhoneSat 2.0.β also flew in the Antares I launch and successfully sent health data of both the smartphone and external sensors.

On November 19 2014, PhoneSat 2.4 was launched, together with other 27 CubeSats, in the Minotaur I rocket from Wallops. The satellite, which was a tech demonstration to perform smartphone radiation survivability and magnetorquers experiments, successfully transmitted sensor data for several weeks and proved the capability of detumbling the satellite.

Currently, PhoneSat 2.5 is scheduled to be launched onboard the Falcon 9 ORS-3 rocket on April 17 2014. This satellite will keep on checking the smartphone survivability and will perform radio and ADCS experiments.

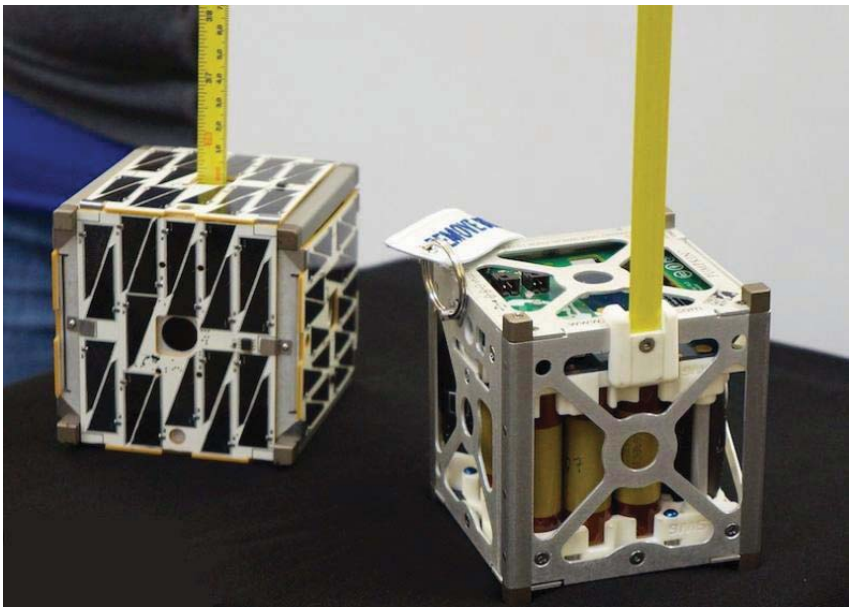

Figure 2: PhoneSat 1.0 and 2.0 models

4.2 PhoneSat 3.X: aiming towards propulsion

Nano-satellite capabilities have continued to grow as the form factor gains popularity. Propulsion is a key enabling system that many CubeSat buses are beginning to incorporate. For example, the focus of the next generation of Ames developed PhoneSat spacecraft (PhoneSat 3.0 series) is to incorporate an interface to these propulsion systems. The interface line to these Spacecraft buses is still to be standardized throughout the community. With PhoneSat 3.0 objectives of investigating feasibility for CubeSat interplanetary travel and attitude control beyond Earth's magnetic field, the interest in propulsion systems is very apparent.

PhoneSat 3.X is currently under design phase and has the propulsion system as one of its main mission goals. The interface for a CubeSat propulsion system is being analyzed from a software, mechanical and electrical points of view.

5 MISSION DEMONSTRATION ANALYSIS

In order to validate the thruster as a valid system for the PhoneSat bus, a first flight demonstration wants to analyze its performance in the easiest possible way. Taking into account the power and lifetime constraints of the CubeSats, the best flight test would be the one that requires low power and can be proven successful in a short timeframe. Three different studies have been done in order to study the space maneuvers that could test the system and to check how the system could be used as a station keeping or deorbit system.

The analysis has been performed using the mechanical properties of the 1.5U EDSN CubeSat designed at NASA-ARC. The three different thruster experiments that have been analyzed are:

- Spin-up test: by installing two thrusters on a single board facing opposite directions, the thruster could be used to spin up the satellite once it has detumbled after P-POD ejection. Using the smartphone gyros, rotational speed could be measured and the experiment would end once sufficient angular speed has been reached. This experiment could be performed several times, and the magnetorquers could detumble the satellite each time the thruster experiment needs to be repeated.

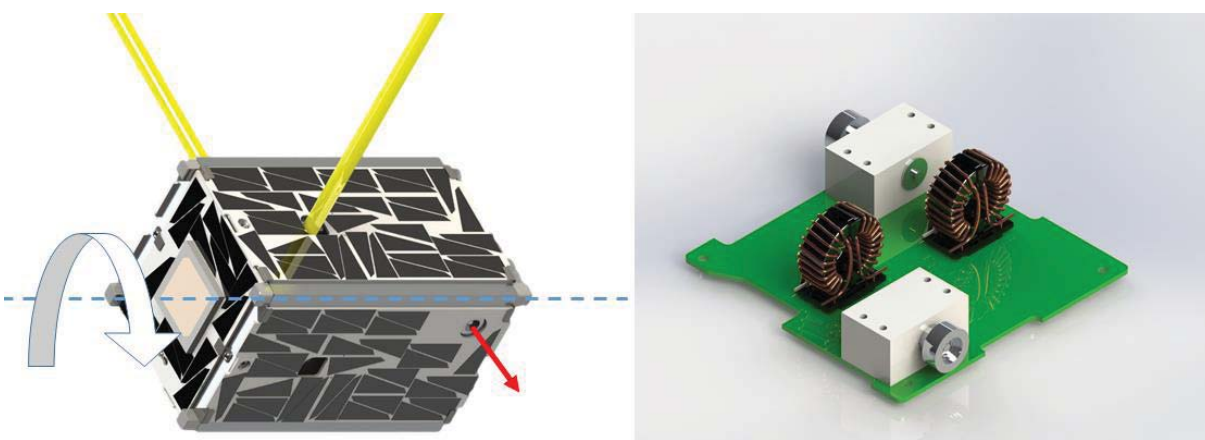

Figure 3: spin-up design configuration

- Station keeping: this would be the most common use of the system for a CubeSat provided it had enough thrust to maintain the orbit or at least increase its lifetime. Several thrusters could be used in parallel to increase the overall thrust if there is enough power available. Two different flight tests could be performed in order to validate the system:

    - Launch two identical CubeSats, use the thruster only on one of them and check that the lifetime can be increased
    - Compare the GPS position of a single spacecraft with the expected position of the same satellite without propulsion system
- De-orbit system: similar to the previous experiment, the system could be used to accelerate the de-orbit time of the CubeSat, and the same flight tests could be done to test the system

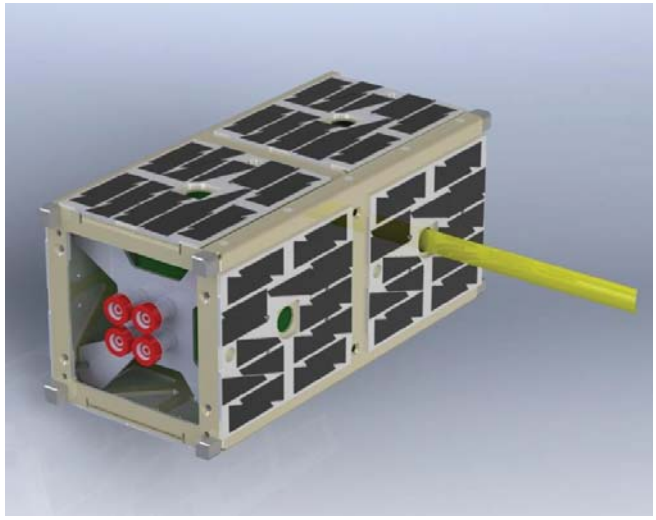

Figure 4: station keeping or deorbiting design configuration

5.1 Spin-up results

This test would consist on, once the satellite has detumbled and self-aligned with the magnetic field, trying to spin it up again along the spacecraft long axis (minimal inertia) and measuring the result using the gyros on board. A target value of 50deg/s of rotational speed was selected to ensure that any residual torque does not lead to ambiguous results. Several analysis at NASA-ARC have been done and the residual torque applied to an EDSN magnetic field aligned satellite would not lead to a rotational speed close to 50deg/s. Depending on the power available, the necessary time to perform the experiment will change. The formula used to calculate the experiment time is:

$$T = \frac{I_{yy}\varpi_{req}\left(P_{bit}+P_{mag}\right)}{I_{bit}P_{av}L} \qquad (3)$$

Where ϖ_{req} is the required rotational speed and equal to 50deg/s, P_{bit} is the power consumption per impulse bit, P_{mag} is the power required to generate the μCAT magnetic field per impulse bit, I_{bit} is the thrust per impulse bit experimentally measured [8], L is the distance between the thruster and the center of gravity of the spacecraft and P_{av} is the available power for the thruster sub-system. The results obtained for the EDSN satellite are shown in Figure 5.

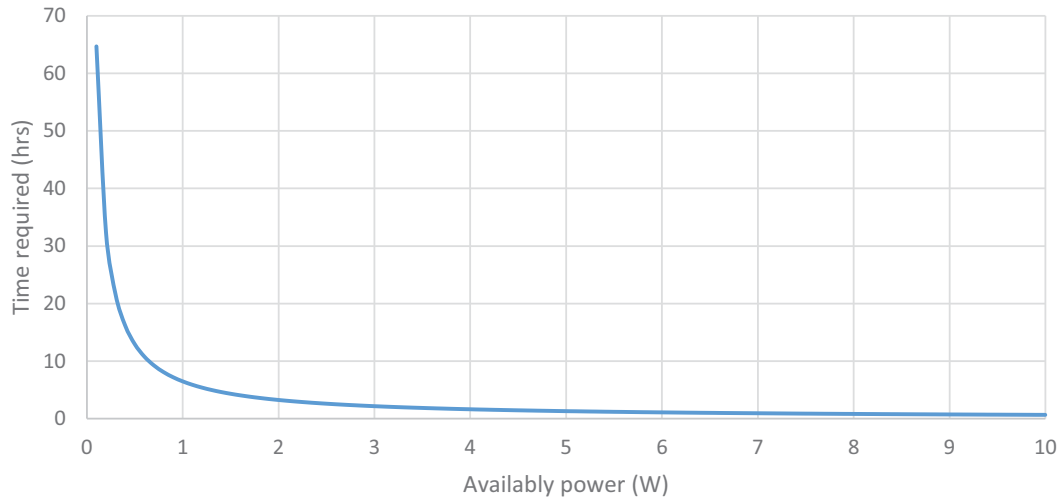

Figure 5: time required for spin-up maneuver vs available propulsion power

If we accommodate 2W to the propulsion system, the overall thruster test could be accomplished in less than 5 hours, which makes it a very safe test to perform in orbit.

5.2 Station keeping results

In this case, the thrusters would be used to provide force to try compensate the atmospheric drag. Figure 6 shows the theoretical necessary power to maintain the orbit for different altitudes using the µCAT propulsion system for a 1.5U EDSN CubeSat:

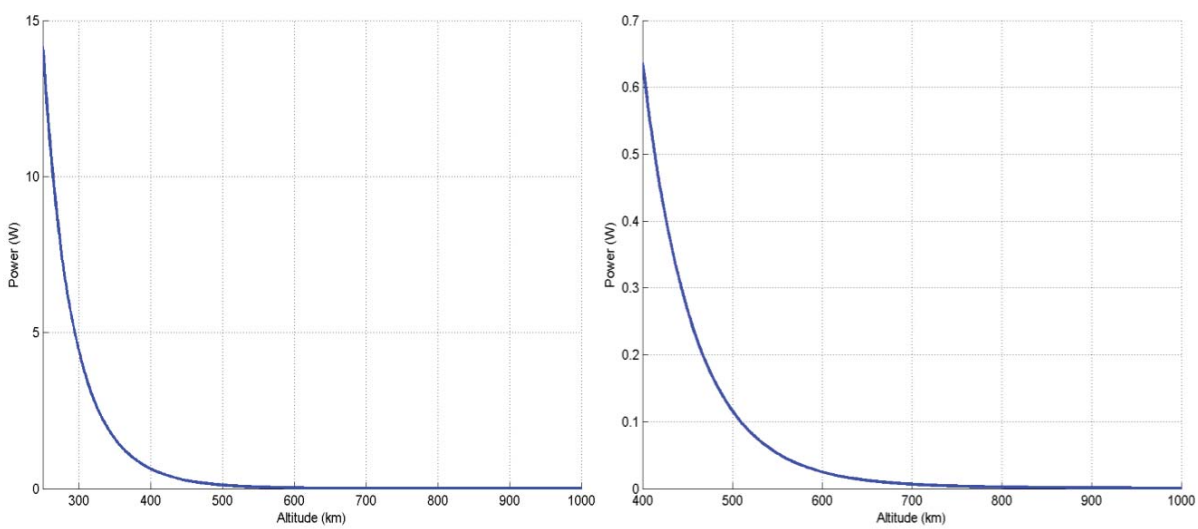

Figure 6: power required for station keeping vs orbital altitude

It can be seen that, for a 400km circular orbit, less than 700mW would be needed to maintain the orbit. A more detailed analysis of the required power to extend the lifetime of a 400km 51deg inclination orbit is shown on Figure 7 and Figure 8.

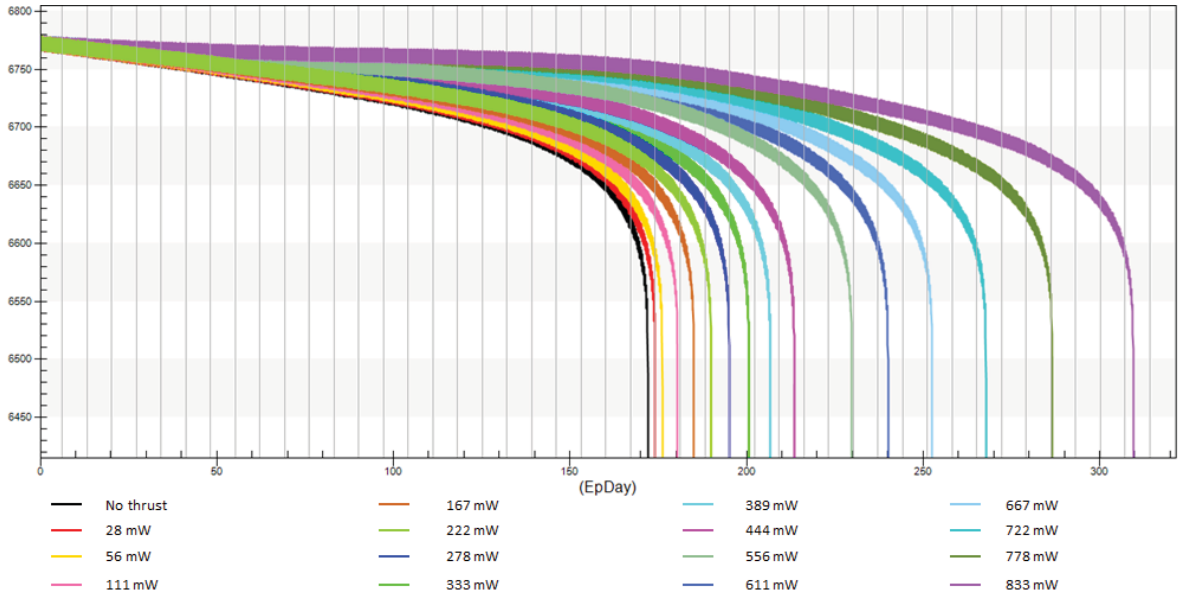

Figure 7: semi-major axis evolution on time for different available thruster power for station keeping

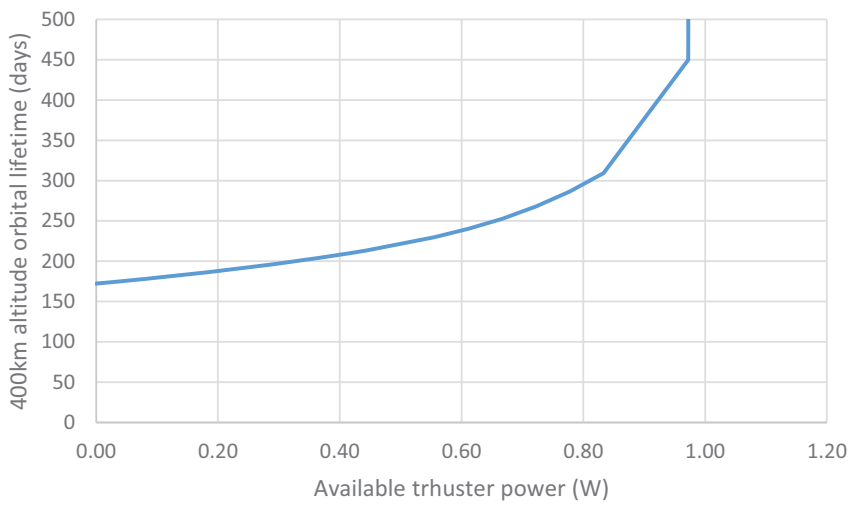

Figure 8: orbital lifetime for different available thruster power

5.3 Deorbiting results

Similar results have been calculated for a deorbit maneuver, and the results are shown in Figure 9 and Figure 10:

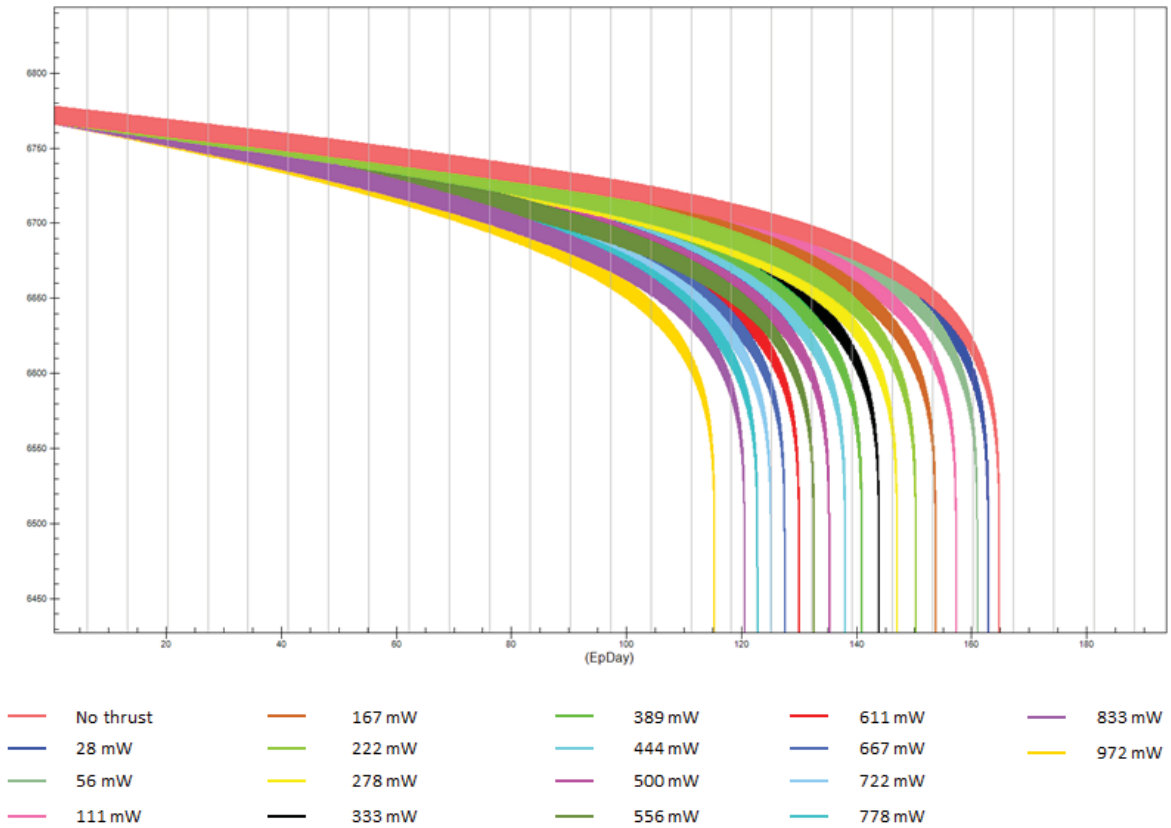

Figure 9: semi-major axis evolution on time for different available thruster power for de-orbiting

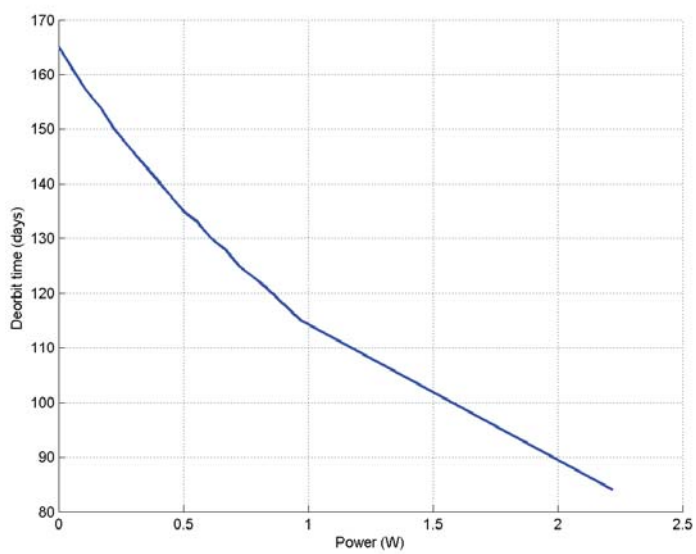

Figure 10: decay time for different available power thruster

5.4 Conclusions

The calculations done in this paper are a first estimate of the power requirements for a potential flight demonstration of the propulsion system. The results are promising but further experimental test is required before a flight demonstration.

From the results obtained in this study, it has been decided that the first technology flight demonstration of the system will consist on the spin-up test because it is the one that would require less operational time and would be the best test to evaluate the flight performance of the system. Atmospheric drag and other perturbations would make it harder to predict the real performance of the thruster in a low-power configuration that aims to extend the orbital lifetime of the satellite. This is why the MAPERS project is focused now on the integration of a single PCB with 2 thrusters aligned in opposite directions that could spin a 1.5U CubeSat along its long, least inertial axis.

However, it has been shown that with low thruster power, the lifetime of a 1.5U CubeSat ejected from the ISS at 400km can be significantly extended. Less than 1W would be needed to double the time in orbit. It can also be seen that the use of the μCAT could be used to quickly de-orbit the satellite once its mission has been accomplished. This is a key maneuver for potential high orbit CubeSats, which currently do not have the capability of a rapid re-entry. Reduction of decay time of more than 30% for a 400km orbit would only require around 1W of thrust power.

6 THRUSTER INTEGRATION INTO THE PHONESAT BUS

For the last year, the Micro-propulsion and Nanotechnology Laboratory (MpNL) of the George Washington University and the MAPERS and PhoneSat teams at NASA Ames Research Center have been working on the potential integration of the μCAT into the PhoneSat bus.

In September 2013, operation of 3 thrusters commanded by a Nexus S using the PhoneSat software platform was successfully demonstrated, and several functional tests of the thruster were conducted at NASA-ARC. After the completion of these first steps, two parallel tasks are now the main focus of the project.

1. Integration of 2 thrusters and PPU into a single PCB that fits into a CubeSat structure (9cmx9cm approximately). This board should have the necessary command and power lines, as well as meet the electrical requirements to be compatible with the PhoneSat bus.
2. Expand the PhoneSat software platform to accommodate a thruster experiment and the right I/O interface with the thruster controller as shown in Figure 11.

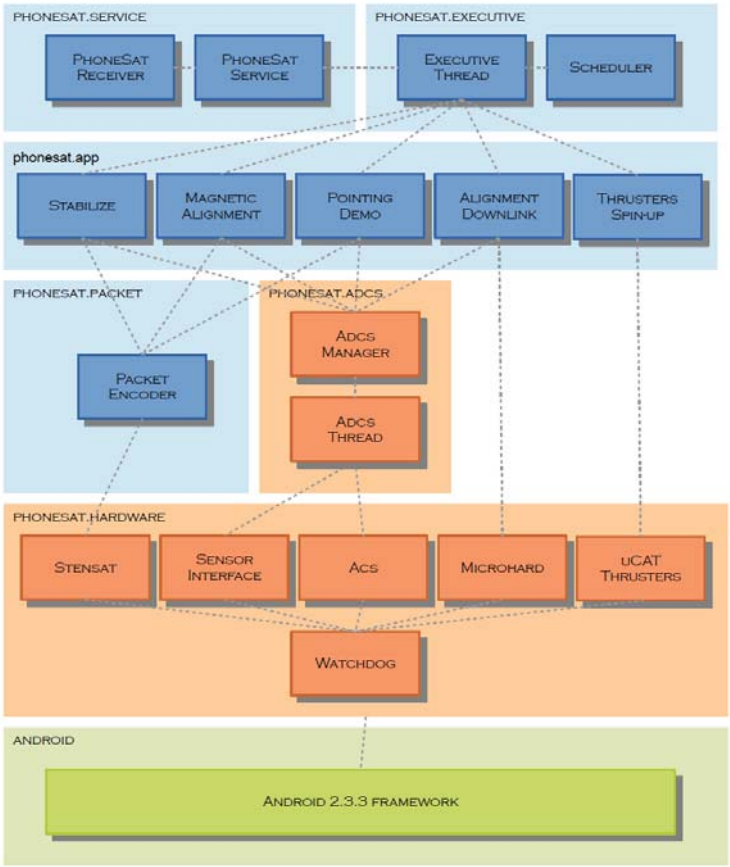

Figure 11: PhoneSat software architecture with the propulsion subsystem module

Right now the PPU control system can be either added to the smartphone software or implemented by an external microcontroller, which would probably be an Arduino.

Once these tasks have been completed, the thruster performance will be tested to determine the expected flight performances of the integrated system. Values of thrust and power consumption of the sub-system are key parameters that will be measured before using the µCAT system as an experimental propulsion system for PhoneSat 3.X.

7 CONCLUSIONS

This paper has presented an overview of the state of the art of CubeSat PPU propulsion systems. The µCAT thruster and the PhoneSat bus have been explained and different potential technology demonstration missions have been analyzed.

The selected mission for a flight demonstration is the use of two µCAT thrusters, controlled by the PhoneSat platform, to spin-up a 1.5U CubeSat and measure its rotational speed with the smartphone gyros. This test can be repeated several times during the mission to characterize the performance of the system.

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